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DUCTILE FRACTURE AND FAILURE CRITERIA OF STRUCTURAL STEELS

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Progress is reviewed for a program which examines aspects of ductile fracture of structural steels. The research seeks to establish multiaxial failure criteria which have sufficient microstructural sensitivity to account for variations in microstructure such that fracture initiation can be predicted. The research involves both experimental and computational analysis. Progress for the period March 1, 1993 to May 31, 1994 is reviewed for (1) the initiation of a study of failure criteria of structural steels and (2) the conclusions of a two-dimensional modeling study of void linking during ductile, microvoid fracture.

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INTRODUCTION

The failure of structural steel components under multiaxial states of stress may be understood at several dimensional scales. On a microscopic scale, failure is usually associated with damage accumulation in the form of voids at locations of large stress and/or strain concentrations, often near an existing crack. On a macroscopic scale, failure occurs when certain conditions based on stress, strain, or combinations thereof are met; i.e., a failure criterion is satisfied. While the development of computational codes capable of predicting stress/strain distributions within structural components under tensile loadings have evolved rapidly in the last decade, the development of improved failure criteria for high toughness components containing small flaws has not. The lack of accurate failure criteria thus frequently limits the ability to accurately predict failure of such structural members. This situation also results in inefficient and costly use of material and reduced system performance.

Using a combination of microscopic and macroscopic approaches, the present research addresses the problem of establishing failure criteria for damage-induced ductile fracture of structural steel components of relatively high toughness and containing small flaws. Our approach is to establish an accurate failure criterion on the basis of not only the macroscopic stress-strain-strain rate conditions associated with "self-propagating" damage but also the microstructural basis of that failure criterion. This, in turn, should serve to establish a failure criterion with the flexibility to take into account local variations of component microstructure, such as near a weldment.

A detailed analysis of microscale damage evolution and its relationship to the load-carrying capacity of a structural component is a central theme of our approach. On a microscopic scale, we expect to observe that, in addition to void interactions among closely spaced voids, void growth and linking collectively undergo an "acceleration" such that damage is sustained, or a crack is initiated, under decreasing applied stresses. Thus we may associate macroscopic fracture initiation with a microscopic level of damage accumulation which, due to void coalescence, is self sustaining. As has been suggested previously[1-3], this is believed to occur at a critical volume fraction of voids, f_c. From a technological standpoint, a realistic failure condition is to recognize that a component will likely lose load-carrying capacity at a critical level of damage defined by f_c. This implies a

macroscopic failure criterion which is based on, and is sensitive to, a microscopically-based fracture initiation process dictated by a critical level of damage identified by the void volume fraction f_c. Unfortunately, little data is available to establish the relationship of f_c to microstructure or stress state. Thus, this research seeks to establish the microscopic basis for a macroscopic failure criterion in order to enable accurate failure predictions of components made of tough alloys, such as HY-100, HY-130, and HSLA-100, containing physically small cracks and with a latitude of microstructures.

On a macroscopic scale, the present research seeks to determine the macroscopic conditions (stress, strain, strain rate) for multiaxial fracture initiation. The fracture criterion, which might be expressed as a map of critical combinations of equivalent strain and mean stress[4,5], will subsequently be established for the microstructural conditions associated with weld metal, and the heat-affected zone of steels of the HY-100, HY-130, and HSLA-100. Identifying the dependence of the criterion on the microstructural aspects of damage, such as f_c, would allow the criterion to take into account new microstructural conditions (or other steels of the same family).

The present study couples closely with applied research within the Naval Surface Warfare Center involving Robert Garrett, John Toeneboehn, Lee Turner, and Mike Vassilaros. Dana Goto, Ph.D. Candidate, is currently the graduate student performing thesis research on this program. In addition, a previous graduate student, Andrew Geltmacher, Ph.D., January 1994, is currently a National Research Council Post-doctoral Fellow at the Naval Research Laboratory performing research in the Mechanics of Materials Section with Dr. Peter Matic. This report describes progress for the period 3/1/93-5/31/94 in which we have (a) initiated a study of failure criteria of structural steels and (b) concluded a two dimensional modeling study of void linking during ductile, microvoid fracture.

PROGRAM PROGRESS

1. FAILURE CRITERIA OF STRUCTURAL STEELS

The principal goal of the proposed study is to determine a failure criterion, and its microstructural basis, for the fracture initiation of welded components of HY-100, HY-130, and

HSLA-100. The failure criterion must be able to relate fracture initiation to the imposed stress and strain states. Our initial assumption is that the criterion may be expressed as failure loci in which the equivalent plastic strain to initiate failure $\bar{\varepsilon}^f$ decreases as a function of stress triaxiality, $\sigma_m/\bar{\sigma}$, where σ_m is the mean stress and $\bar{\sigma}$ is the equivalent stress.[4,5]

Testing to determine the failure loci will be performed initially on HY100 steel base plate using axisymmetric smooth ($\sigma_m/\bar{\sigma} \cong 0.5$) and two notched geometries with $\sigma_m/\bar{\sigma} \cong 1.1$ and $\sigma_m/\bar{\sigma} \cong 1.5$. Finite element analysis, performed with the assistance of Mr. Lee Turner of NSWC at White Oak, is being used to determine the actual values local stress states and strains within the notched and unnotched bars. The notched bars currently being investigated have notch diameter-to-notch radius ratios of 1:1 and 2:1, which are referred to as the A-Notch and D-Notch configurations, respectively. Examples of the results of our recent computations which predict spatial dependence of the $\sigma_m/\bar{\sigma}$ -values for smooth and notch specimens is shown in Figure 1. It should be noted that the mean stress used in Figure 1 was calculated by using the hydrostatic pressure, which is negative for a positive stress. Thus, the $\sigma_m/\bar{\sigma}$ values are negative.

The stress and strain distributions within the samples such as those shown in Figure 1, will be used in conjunction with metallographic examination of axially cross-sectioned, deformed or fractured tensile bars to quantitatively describe the onset of damage (void nucleation), and the subsequent propagation of the damage to failure (void growth and coalescence). Given the spatial distribution of the stress states shown in Figure 1, care must be taken to identify not only the damage characteristics but also the physical location of the damage being characterized. A procedure which utilizes limit curves or zones of damage will be used to quantitatively characterize accumulated damage. In addition, the locus of strain-stress state combinations ($\bar{\varepsilon}$-$\sigma_m/\bar{\sigma}$) defining macroscopic fracture will be determined. These strain-stress state combinations will be used to generate a failure map and to calibrate computational damage models, as well as to serve as failure conditions for computational codes predicting structural deformation and fracture.

By correlating microstructural observations of damage accumulation to computationally derived stress and strain conditions, arbitrarily assigned best-fit parameters employed in most previous

ductile fracture studies can be replaced by microstructural-based quantities. For example, it is anticipated that for HY-100 steel the inclusion volume fraction and void volume fraction at fracture will provide the basis of these microstructural-based quantities. Specifically, the inclusion volume fraction and mean spacing is anticipated to provide the basis for the definition of a characteristic volume of material over which failure must occur in order to satisfy a ductile fracture criterion. As described earlier, the void volume fraction at failure initiation, f_c, is also a critical factor in predicting fracture. In the past, the magnitude of f_c has been assigned values about, 0.15, irregardless of the microstructure or stress state. No experimental verification of the critical void volume fraction has yet been performed for any structural alloy, including HY-100.

At the present time, we are in the process of machining HY-100 specimens with the A-Notch and D-Notch configurations as well as the unnotched configuration. In addition, right cylindrical compression samples are also being prepared in order to obtain large strain data for subsequent finite element analysis.

2. A MODELING STUDY OF THE EFFECT OF STRESS STATE ON VOID LINKING DURING DUCTILE FRACTURE

Increasing the triaxiality of the applied stress state normally decreases the fracture strain of structural alloys. For alloys failing due to damage accumulation in the form of microvoids, this dependence implies a sensitivity to void nucleation, void growth, and/or void linking to the imposed stress state. The strain to nucleate voids has been shown to decrease as the triaxiality of the stress state increases. Both experiments and analyses indicate that the growth rate of voids increases rapidly as the degree of stress triaxiality increases. In contrast, the influence of stress state on void linking is not well established.

In a recently completed program, we examined certain features of three-dimensional void linking by two-dimensional modeling using sheet specimens containing arrays of through-thickness holes. We, and others[6-8] believe that hole interaction effects in two dimensions are more pronounced than void interaction effects in three dimensions. In the current research, hole interaction effects are further enhanced by the use of sheet specimens, which are known to be very

susceptible to flow localization and localized necking phenomena. Thus, the current results relate most directly to the form of void linking which occurs due to plastic flow localization within the intervoid ligaments. The "void sheet" process[9-11] is a good example of such a void linking phenomenon, as are cases where planes of locally high void (or pore) content can trigger void linking due to deformation localization.[12,13]

With the above void linking characteristics in mind, we propose that three-dimensional void linking (due to flow localization) is sensitive to stress state as follows:

(1) The initiation of void linking between neighboring voids is retarded by stress triaxiality. The results of the present study suggest that a larger macroscopic level of strain is needed to develop flow localization in the intervoid ligament for a given void spacing and matrix strain hardening as the degree of triaxiality is increased; see Figure 2.

(2) The propagation of void linking is promoted by high degrees of stress triaxiality, resulting from the increasingly multidirectional nature of the void linking paths; see Figure 3. This assumes a spatially uniform stress and strain field which does not to bias the fracture plane. Thus, void linking will be governed primarily by intervoid spacing (and size) at *high* triaxiality; such void linking is expected to be "efficient", involving a high fraction of available voids. In contrast, the propagation of void linking under uniaxial strain conditions depends on both the directionality of the linking path and the spacing to the nearest favorably oriented void. This results in a directional void linking path in uniaxial tension. As a result, void linking should be gradual with considerable damage accumulation in the form of void growth, local flow instabilities, and ligament fractures before specimen failure. Previous experimental results support such a hypothesis.

(3) Void linking is promoted by void clustering in both uniaxial and equal-biaxial tension, as is shown in Figure 4. The present results do not indicate whether or not void clustering accelerates void linking even more as stress triaxiality increases.

(4) Void linking is inhibited by the material strain-hardening capability, as is depicted in Figure 5. This is due to the ability of a material with a high strain-hardening exponent to diffuse

the strain around the holes. As a result, a larger applied macroscopic strain will be needed to cause flow localization and failure of the ligaments between voids.

In summary, our experiments suggest that much of the dependence of "flow-localization-induced" void linking on stress state can be understood in terms of the directionality of void-linking paths. The number of viable linking paths increases with increasing stress biaxiality. The linking path issue influences the "efficiency" of the void linking process and thus the ease with which accumulated damage is self propagating. It also suggests that, once voids nucleate, the propagation of void linking and fracture can occur within a small strain increment at high levels of stress triaxiality. As such, the material becomes less tolerant to internal damage. Increasing matrix strain hardening and inhibiting void clustering will retard the onset of such a void linking process and effectively enhance fracture resistance.

REFERENCES

1. L. M. Brown and J. D. Embury in Proc. 3rd Int. Conf. on Strength of Metals and Alloys, 1973, p. 164.
2. V. Tvergaard and A. Needleman, Acta Metall. 32, 157 (1984).
3. A. Needleman and V. Tvergaard, J. Mech. Phys. Solids 32, 461 (1984).
4. J. W. Hancock and A. C. Mackenzie, J. Mech. Phys. Solids 24, 147 (1976).
5. J. W. Hancock and D. K. Brown, J. Mech. Phys. Solids 31, 1 (1983).
6. S. H. Goods and L. M. Brown, Acta Metall., 27, 1 (1979).
7. C. L. Hom and R. M. McMeeking, J. Appl. Mech. 56, 309 (1989).
8. P. F. Thomason, private communication, 1993.
9. T. B. Cox and J. R. Low, Metall. Trans. 5, 1457 (1974).
10. J. W. Hancock and A. C. Mackenzie, J. Mech. Phys. Solids 24, 147 (1976).
11. G. T. Hahn and A. R. Rosenfeld, Metall. Trans. 6A, 653 (1975).
12. R. J. Bourcier, D. A. Koss, R. E. Smelser, and O. Richmond, Acta Metall. 34, 2443 (1986).
13. R. Becker, J. Mech. Phys. Solids, 35, 577 (1987).

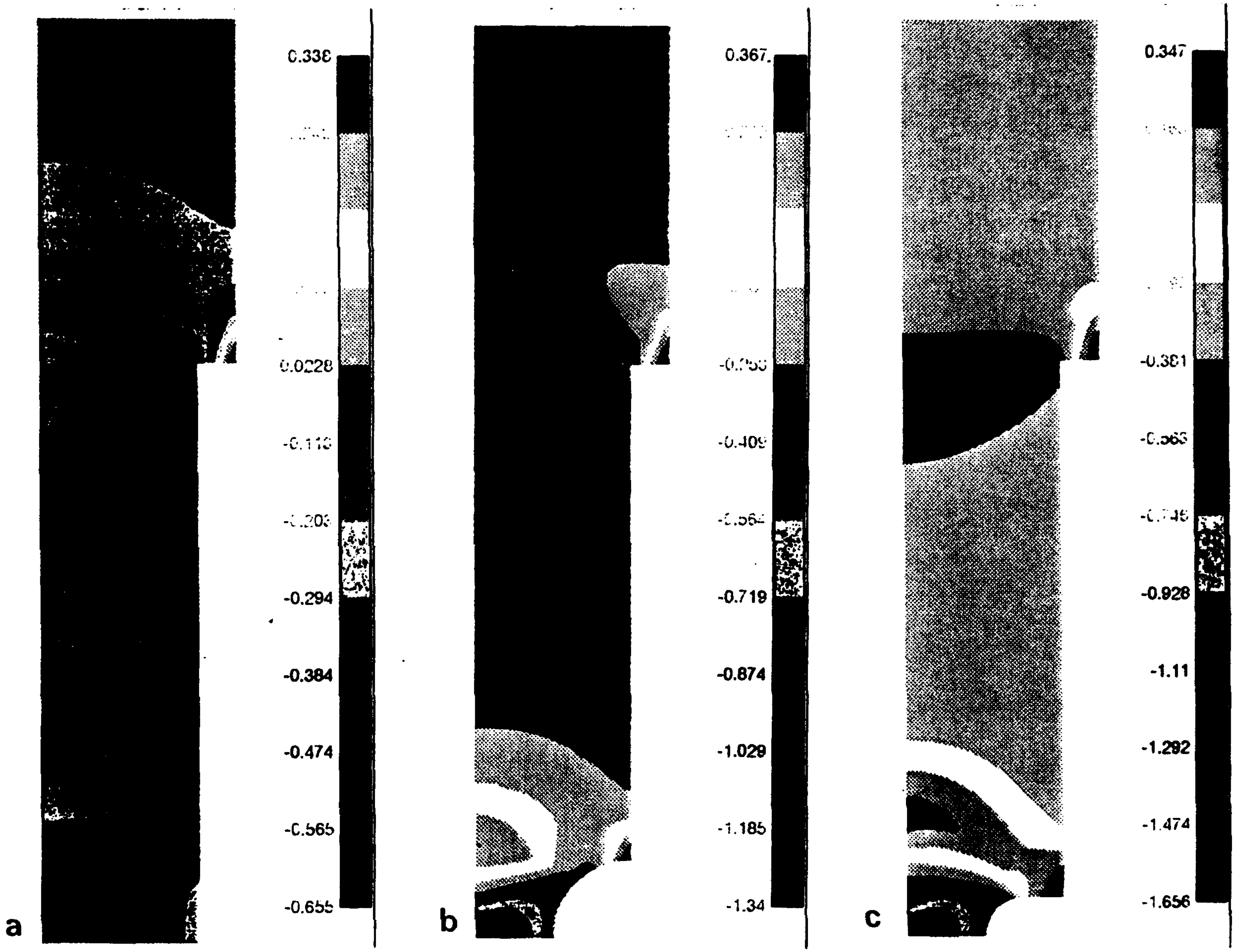

Figure 1. Contours of stress triaxiality, $\sigma_m/\bar{\sigma}$ for axisymmetric tensile specimens which are (a) unnotched and deformed 0.070, (b) notched with notch diameter/radius = 1 and deformed 0.015, and (c) notched with notch diameter /notch radius = 2 and deformed $\bar{\varepsilon}$ 0.030.

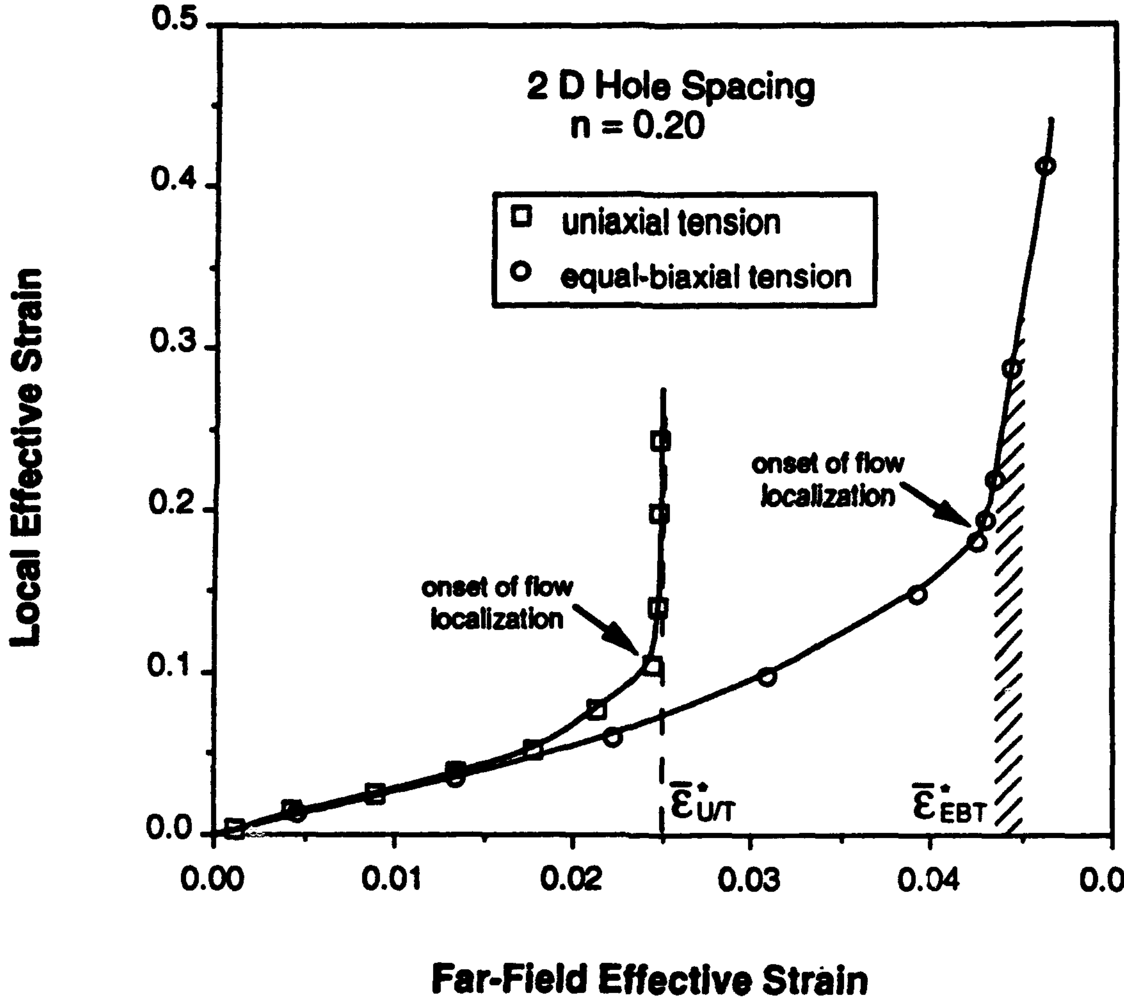

Figure 2. Computational predictions of the evolution of "local" effective strains within an element centrally located between a pair of holes as a function of the imposed fair-field effective strain.

a)

b)

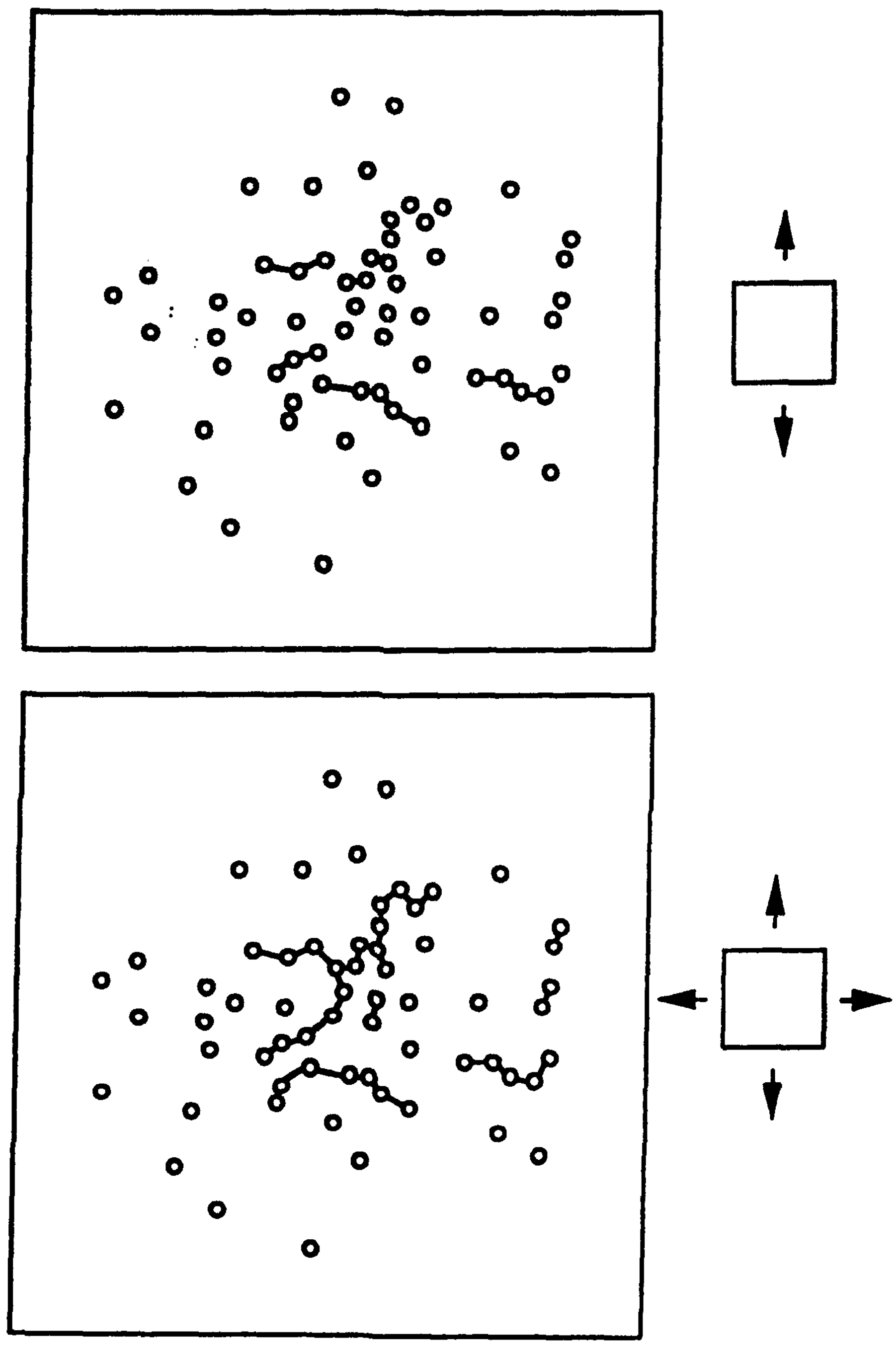

Figure 3. The flow localization paths developed in specimens with a minimum allowable hole spacing of one hole diameter and tested in either a) uniaxial tension or b) equal-biaxial tension. The tensile axis is vertical for the uniaxial case.

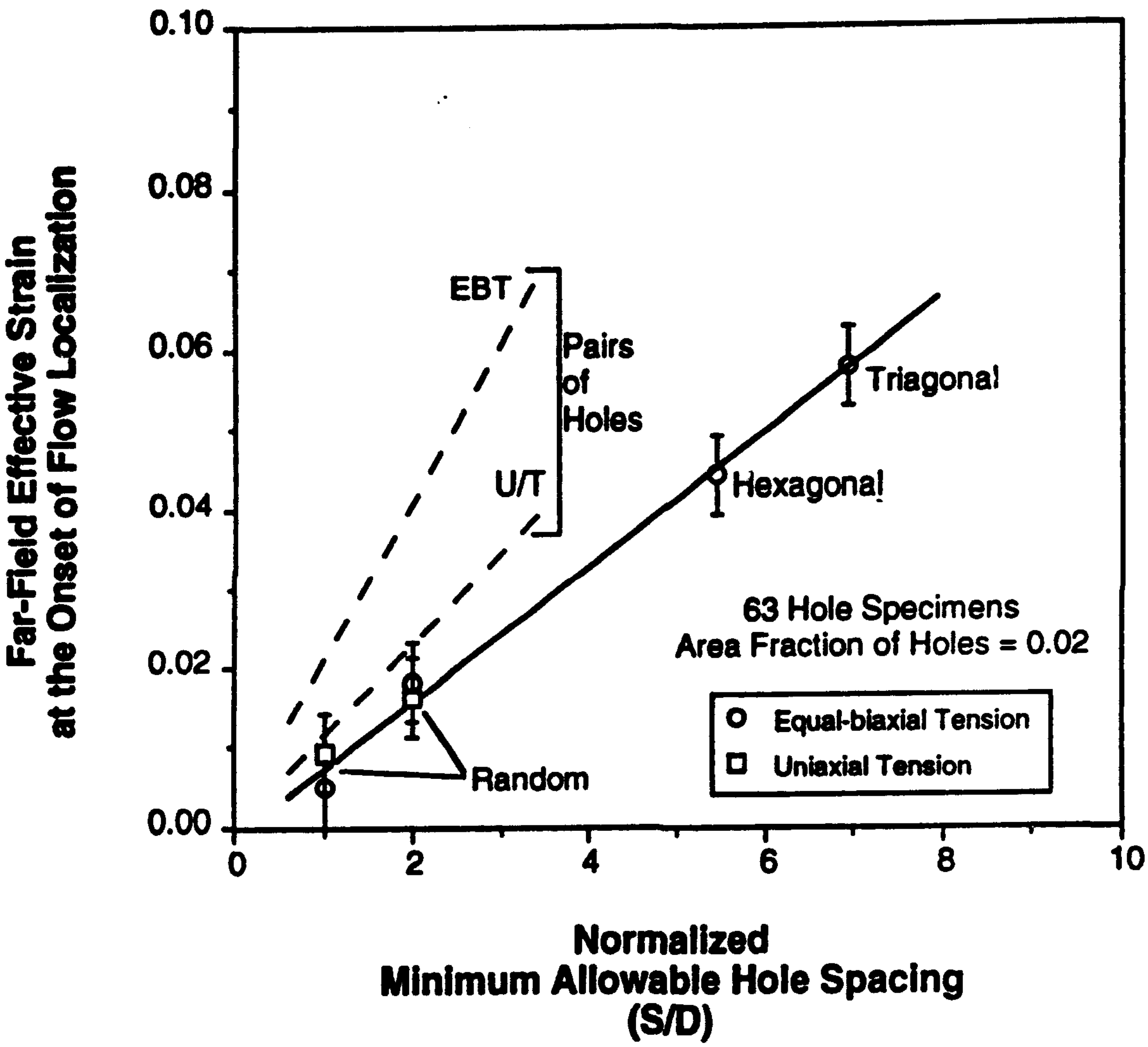

Figure 4 The effect of minimum interhole spacing, S, normalized by hole diameter, D, on the far-field effective strain at the onset of flow localization between holes. The hexagonal and trigonal arrays are regular arrays. Decreasing S/D acts to increase hole clustering. EBT denotes equal-biaxial tension, and U/T denote uniaxial tension.

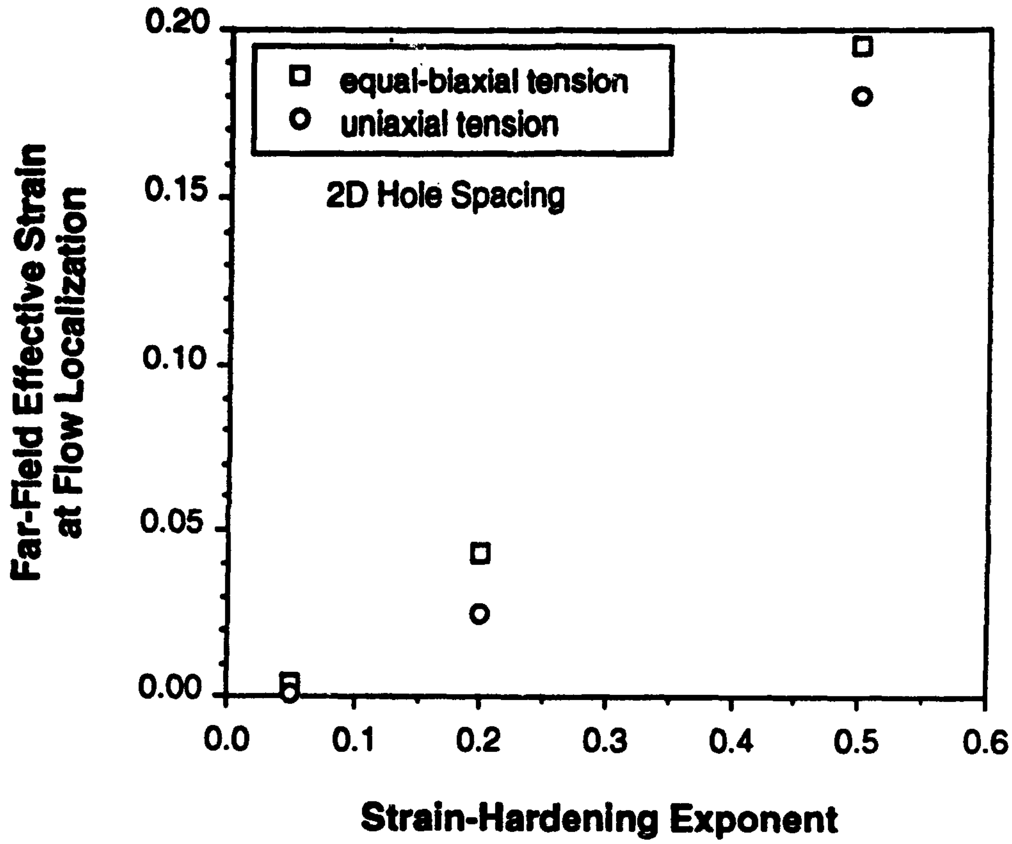

Figure 5. The dependence of the far-field effective strain at the onset of flow localization on strain-hardening exponent for uniaxial and equal-biaxial tension. Data are computed for localization at an element located at the center of interhole ligament.